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Engine-Level Simulation of Liquid Rocket Combustion Instabilities

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Douglas G. Talley
Douglas.Talley@edwards.af.mil

Suresh Menon
Suresh.Menon@ae.gatech.edu

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Engine-Level Simulation of Liquid Rocket Combustion Instabilities

A numerical investigation into combustion instability in liquid rocket engines is undertaken using large eddy simulations (LES). HPCMP resources have been applied to demonstrate the ability to simulate combustion instability in liquid rocket engines and to gain further understanding of these complex phenomena. Specifically, simulations have been used to uncover the unsteady instability mechanism in a single-element injector. Results show that it is a combination of three events that lead to the instability and the timing of the events are critical. A second investigation has begun to apply LES to multi-element injectors, which require significant resources. Finally, an investigation into the use of approximate boundary conditions, relevant to multi-element injectors, showed that caution must be used when applying approximate boundary conditions. The results show that approximate boundary conditions led to different heat release locations and mixing downstream of the boundary.

1. Introduction

Modeling turbulent combustion in liquid rocket engines (LRE) is one of the main research challenges for the aerospace community. These engines produce a colossal amount of energy in a confined volume, more than 10 GW/m³. With this high of an energy density, there is a high-likelihood of combustion instabilities occurring. Combustion instabilities are organized, oscillatory motions sustained by combustion. Its occurrence is difficult to predict, and it remains a major obstacle in the design of rocket engines despite six decades of active research. The present paper reports the results obtained during the second year of the Challenge Project, the objective of which is to simulate multi-element combustion of liquid oxygen and methane.

Combustion instability simulations require unsteady reacting flow simulations with highly refined meshes. The HPCMP resources provided by the Challenge Project have allowed several numerical investigations to be undertaken this year, each investigation requiring multiple simulations. These include the identification of the instability mechanism in a single-element engine, a detailed study on the importance of the inlet boundary conditions, and initial work on simulating a multi-element configuration. Two MPI based parallel finite-volume CFD codes were utilized, LESLIE3D, a structured multi-block solver developed at the Georgia Institute of Technology and GEMS an unstructured solver developed at Purdue University. Details of each code's capabilities and its scaling have been reported in the past and are avoided here, for brevity.

Large Eddy Simulations (LES) can provide additional information including velocities, combustion heat release, and species concentrations not available from experimental results. Once validated the simulations offer an opportunity to explore what is happening in the combustor by visualizing and analyzing the temporally and spatially resolved flowfield. Simulations use between 500,000 and 25 million grid points and are run for tens of milliseconds with time steps less than 0.1µs. Each simulation typically uses at least 1000 CPUs and has CPU hour requirements greater than one million hours. Data storage requirements are in excess of 1 TB per simulation. Multiple simulations have been conducted simultaneously because of the availability of HPCMP resources. HPCMP resources have also allowed a greater percentage of the simulations to be in three-dimensions, which are more expensive, by at least an order of magnitude in CPU hours, but are more physically realistic.

2. Results

I. Examination of the Inlet Boundary Condition

In rocket engines, combustion instability can be strongly influenced by acoustic interactions at the boundary. It is therefore important to use accurate representations of the boundary conditions. Approximate boundary treatments are often desirable in order to limit the regions of the domain that must be modeled or to simplify complex geometric structures. In this study, two inlet boundary conditions have been simulated for a combustor that shows sustained high-amplitude combustion instabilities. The two inlets considered are the actual complex choked slot boundary and a uniform constant mass flow boundary condition that approximates the choked flow inlet. For the three-dimensional simulation, the detailed boundary condition required approximately 20 percent

more grid points, 5.0 million versus 4.2 million grid points. A 20 percent increase in grid points corresponds to approximately a 20 percent increase in the CPU hours required which is significant. The exact boundary requires also more preprocessing time to construct the mesh. Figure 1 shows a slice of the grid points near the boundary for both cases.
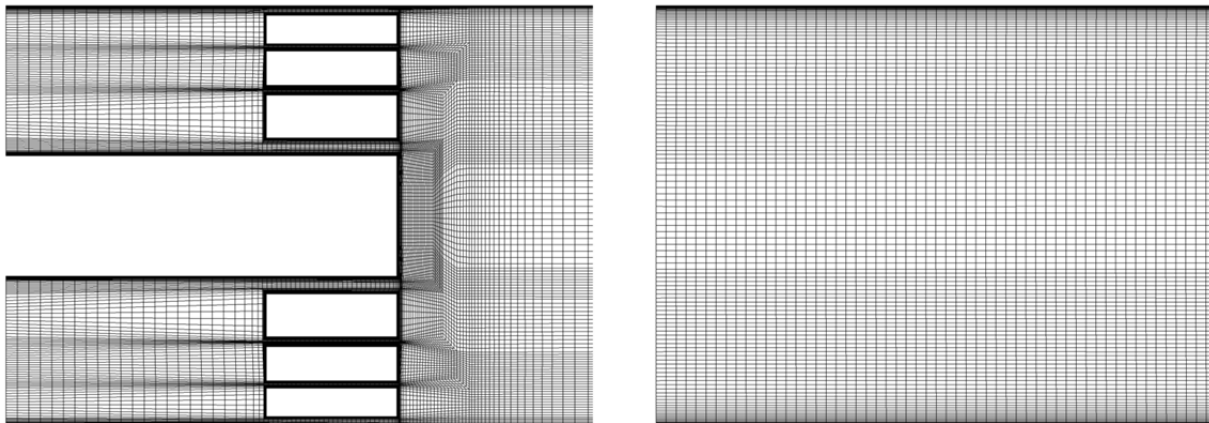
Figure 1: Grid in the region near the oxidizer inlet for the exact boundary (left) and the uniform constant mass flow boundary (right).

Both boundary conditions are able to predict unstable behavior in the combustor with the constant mass flow inlet showing higher levels of instability. The simulations show that the constant mass flow boundary is not accurately able to predict the third mode of the instability. Figure 2 shows the pressure modeshape for the first three modes. In the figure, we see that the first two modes are very similar between the two cases. For the third mode, the behavior is very different with the exact boundary condition showing significantly higher amplitude oscillations. This study has shown that some aspects of the flowfield such as the first two acoustic modes are well captured while higher harmonic modes are not as well represented. There is a large amount of vorticity generated by the vortex shedding at the slots that is absent in the constant mass flow boundary simulation. This vorticity influences the flowfield in the combustor altering the mixing of the fuel and oxidizer. Figure 3 shows the time-averaged vorticity magnitude downstream of the slots in the combustion region, the heat release is outlined in black. The differing levels of vorticity in the two simulations produce different heat release patterns with the constant mass flow boundary producing having concentrated levels of heat release. These results suggest that such boundary condition approximations must be used carefully, only in combination with more detailed study of the boundary condition. This use of approximate boundary conditions is important as we start to look at simulating larger multi-element engines; in this case using the complete geometry for 100's or 1000's of injectors is not practical.

II.   Instability Mechanism Identification

Figure 4 shows a snapshot of the unsteady flowfield for a single element engine. The figure shows some of the complex features of the flowfield including the high Mach number flow near the oxidizer injector, the three-dimensional temperature field in the combustor and the interaction between the fuel and heat release near the expansion. A combination of complex physical phenomena is often responsible for the instability making the identification of a mechanism challenging. Three different conditions were simulated in three-dimensions; each condition, corresponding to a different oxidizer post length, shows a different level of instability.
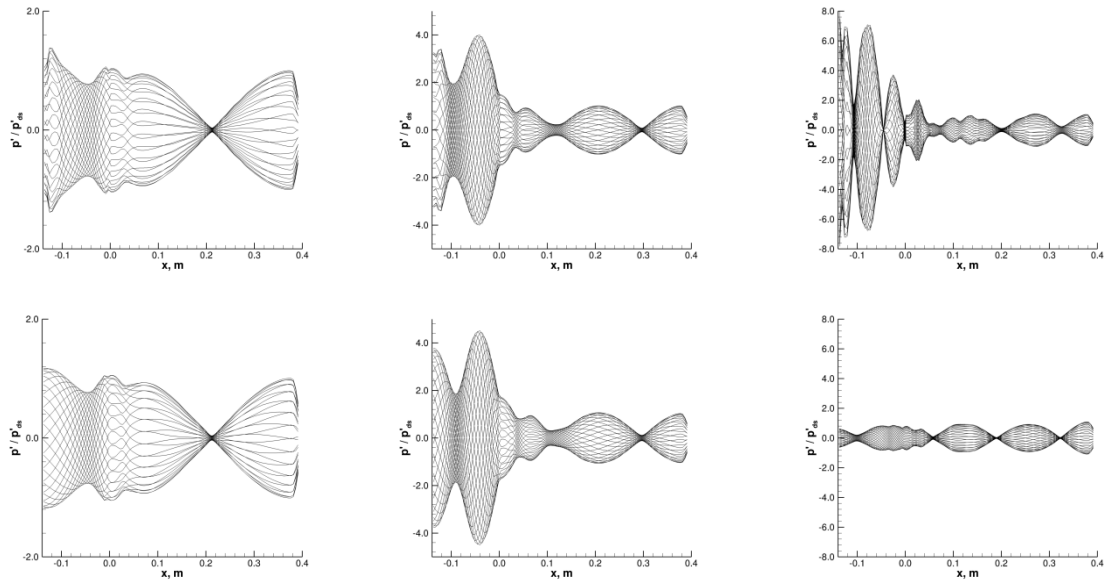
Figure 2: Pressure mode shape for the first three longitudinal modes for the case with slots (top) and the uniform mass flow inlet (bottom).
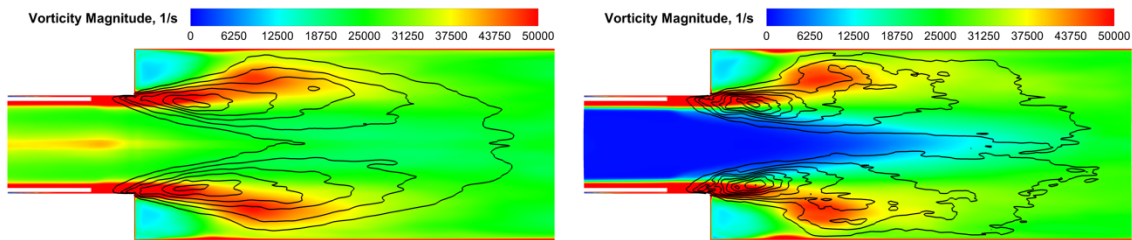

Figure 3: Time averaged vorticity in the combustion region. The simulation with slots is shown on the left and the simulation with the constant mass flow boundary is on the right.
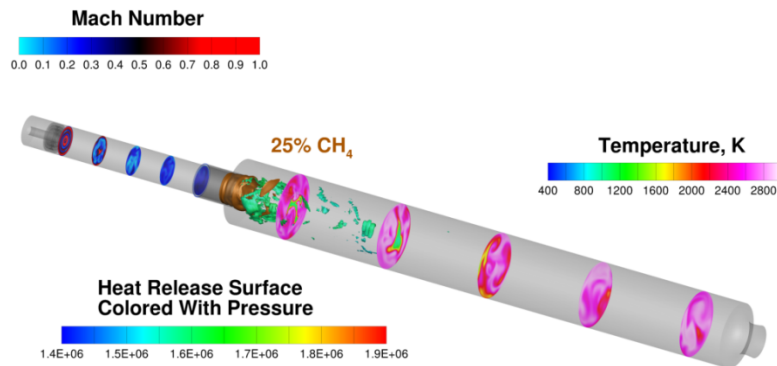

Figure 4: Slices in the oxidizer post (left) are colored with the Mach number; notice the high Mach region near the injector. Slice in the combustor (right side) are colored with temperature. Near the expansion is an iso-surface of 25% fuel and the combustion heat release.

Using the results of the simulations, we have determined that the instability is a result of the combination of three phenomena, the timing of the acoustic waves in the oxidizer post, the mixing of the fuel and oxidizer near the injection point, and the existence of a triple flame structure (a region of intense combustion). In the unstable case, the three events result in a cyclic process where fuel is starved from the combustor allowing the combustion to dwindle and move downstream away from the injection region. As the amount of combustion decreases fuel, which is not burning, accumulates in the combustor. Once the accumulated fuel is reignited, a massive amount of heat release occurs. This heat release coincides with the acoustic waves in the combustor and further amplifies the pressure. This large pressure rise sets up the fuel starvation event for the next cycle. The entire process is very repeatable as the simulation progresses, each cycle lasts less than 1 ms. Figure 5 shows a surface of fuel and heat release in the combustor before and after reignition takes place. Notice that before reignition takes place the heat release is downstream and the upstream region adjacent to the expansion is filled with fuel. After reignition, the heat release moves upstream and consumes the available fuel.
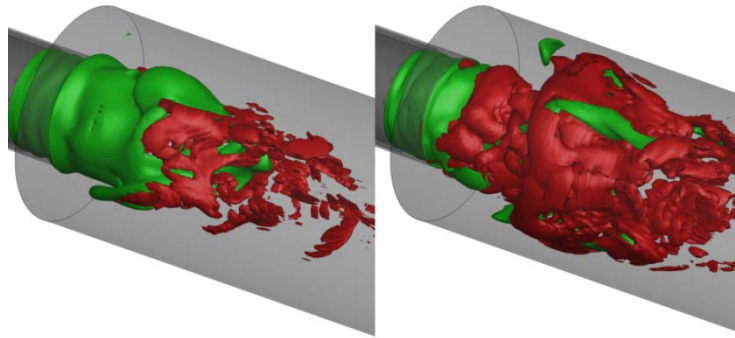
Figure 5: Heat release (red) and methane (green) in the combustion region. Image on the left shows methane filling the combustor and heat release downstream, the image on the right shows the heat release moving upstream consuming the available methane.
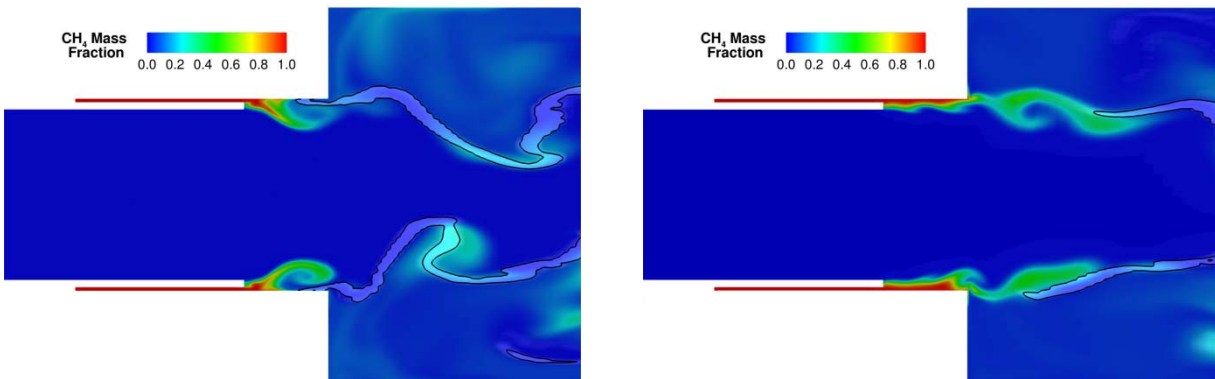

Figure 6: Flow near the injector for an unstable case (left) and a stable case (right). The unstable case shows the fuel mass fraction pushed away from the wall and heat release, outlined in black, occurring near the wall. In the stable case, the flow of fuel into the combustor is uninterrupted.

In the stable case, the three phenomena leading to instability are still present but are not well correlated. The difference in timing for the events results in a steady supply of fuel into the combustor. With a steady supply of fuel, the heat release is continuous and exhibits only a minor coupling with the pressure. The large reignition events, which help to drive the large-scale pressure oscillations, are absent. Figure 6 shows the creation of the fuel starvation region upstream of the expansion. In the unstable case the pressure wave moving through the combustor disrupts the incoming flow, increased mixing in the region due to misaligned pressure and density

gradients creates a partially premixed region, which supports combustion. The combination of the disrupted flow and combustion consuming the available fuel leads to the temporary starvation. In the stable case, a steady supply fuel is fed into the combustor is visible.

III.   Multi-element Study

Before considering multi-element injectors, it is important to understand the physics of a single element. A single injector test case is used as a baseline for the multiple element simulations. The focus is on obtaining a stable combustion with LOX-CH4 for this configuration and evaluating the grid quality required for the future scale-up studies. The isometric surface in Figure 7a shows the flame front and the corresponding temperature and Fig. 7b shows a 3D isometric view of the temperature iso-contour in the combustion chamber. The single injector simulations flow through time is approximately 10 ms and multiple flow through times have been simulated. No slip and adiabatic conditions are applied at the wall of the chamber. Overall features of the flame stabilization in the shear coaxial injector are visible. In the near field of the injector, a very thin diffusion flame is anchored at the LOX post tip followed by a larger region of distributed burning. While pressure fluctuations are observed, there are no large-amplitude oscillations. This result is encouraging since the test conditions being simulated is for a stable combustion. The results of the single-element injector will be used to guide the simulation of a 3-injector test case.
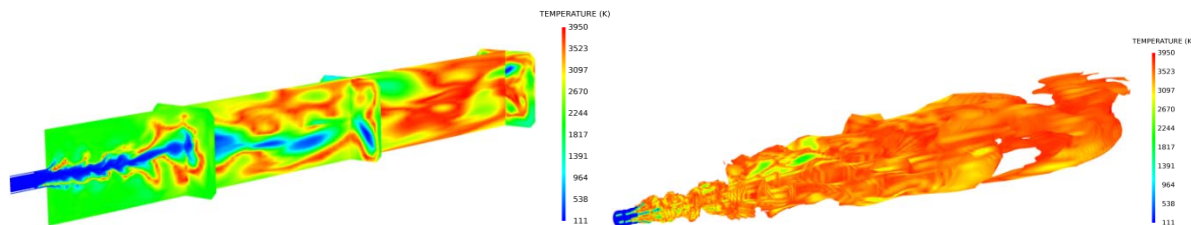
Figure 7.   Single Injector Test Case.   (a): Instantaneous temperature contours, (b): Iso-contour surface at stoichiometric mixture fraction with temperature color map

A 10-injector case is being used to look at injector-to-injector interactions and to contrast the similarities and differences of the single injector case. Although 2D, many features of interest here are similar to the actual test case. The test condition mimics the actual setup and uses real gases with finite-rate kinetics. The temperature color map in Figure 8a shows the interaction between injectors and the compressibility color map shows the effects of real gas physics. The flow through time is approximately 3 ms and the flow has been simulated for multiple flow-through times. This is one of the first reported LES simulations of a multi-injector flowfield with real gas kinetics.

It can be clearly seen that even though all injectors are modeled using identical inflow conditions and grid resolution there are substantial injector-to-injector effect almost immediately. A video of the time-sequence clearly shows that the shear layers interact with the adjacent injectors. These interactions take place 2-3 diameters downstream where the flame is very thin and diffusion is critical. An analysis of the compressibility, Figure 8b, shows that these interactions occur where compressibility is very high (< 1 indicates regions of real gas effects). There are pressure oscillations in both axial and transverse directions; however, their magnitude may not be reliable since these are 2D simulations.
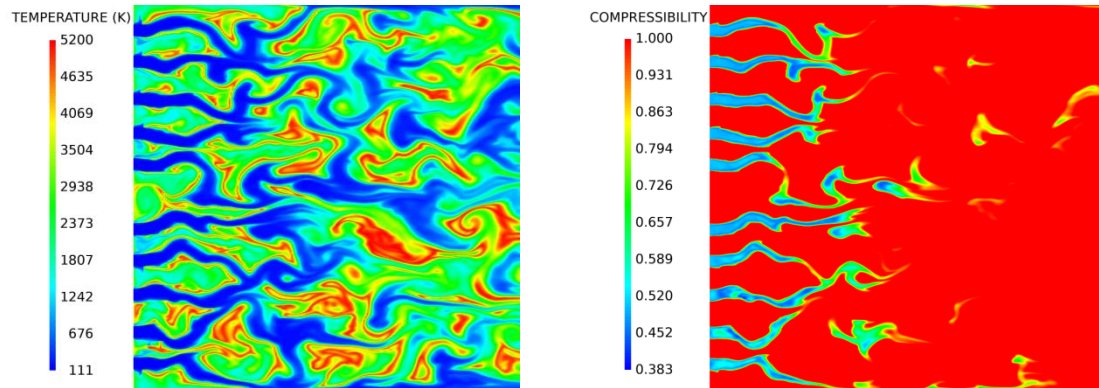
Figure 8. 10-injector case: (a) Temperature, (b) Compressibility.

The three injector case is being run as a first step towards a full multiple element simulation. The injectors are configured in the same manner are the single injector case and the flow conditions are identical except for a larger combustor domain. The grid, shown in Figure 9, contains about 25 million mesh points.
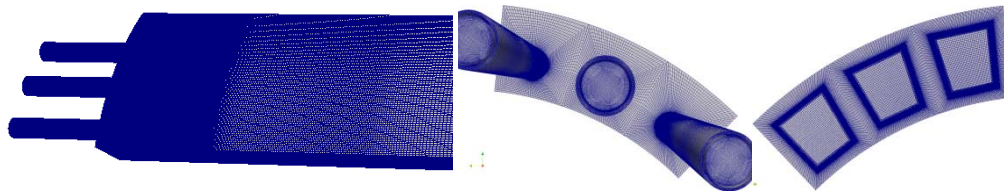
Figure 9. Grid for the three-injector case.

3. Conclusions

This project directly supports the ALREST combustion instability program. Combustion instability is a serious risk to the development of liquid rocket engines for the Air Force. HPCMP resources have been applied to gain a further understating of combustion instability and to demonstrate the ability to apply LES to the environment inside a liquid rocket engine. The instability mechanism of a single element rocket engine was determined using numerical results from multiple simulations. The instability is the result of a combination of three events; the timing of the events is critical. A second investigation into applying LES to multi-element injectors showed that injector-injector interactions are important and can influence where combustion takes place. An investigation into the use of approximate boundary conditions showed that caution must be used when applying approximate boundary conditions because of downstream effects on the flowfield. Increased understanding of the mechanisms of combustion instability and the ability to apply simulations to actual rocket engines will improve the design of liquid rocket engines, which is currently dependent on expensive sub-scale and full-scale testing. The HPCMP resources provided by the Challenge Project were integral in obtaining these results allowing for more simulations and larger cases to be undertaken.

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